Classification of Intentional Electromagnetic Environments (IEME)

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Note

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Classification of Intentional Electromagnetic Environments (IEME)

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Abstract— **One can classify potential IEME threat environments into four categories, based on frequency coverage. Yet another way of categorizing IEME environments is based on the level of sophistication of the underlying technologies involved in producing the EM environment, as low, medium and high-tech systems. A third way of classifying IEME is by the effects that it can have on a targeted system. This paper will examine the merits of classifying IEME in these ways and provide examples of HPEM generators that employ current and emerging technologies, for each classification scheme**.

***Index Terms*— Intentional EMI, bandratio, High-Power Electromagnetics (HPEM), threat environments**

I. Introduction

In present day society we are increasing our reliance on widespread technological advancements in computer and electronic systems. The diverse activities of civilized societies, such as, civil defense, air-traffic safety and control, police, fire departments, ambulances, hospitals, communication and commerce are becoming more and more dependent on these advanced technologies. While this dependence on technology increases the level and quality of the services that can be offered to the general public, this sophistication comes at the price of an increased vulnerability to a wide variety of threats that can pose as threats to the society's infrastructure.

It is well established that sufficiently intense electromagnetic (EM) signals in the frequency range of 200 MHz to 5 GHz can cause upset or damage in electronic systems. This induced effect in an electronic system is commonly referred to at intentional electromagnetic interference (IEMI).

Such an intentional electromagnetic environments (IEME) can be described in a variety of ways. For example, the disturbing EM environment could be described by attributes of the incident field applied to a system as

- a single pulse with many cycles of a single frequency (an intense narrowband signal that may have some frequency agility),
- a burst containing many pulses, with each pulse containing many cycles of a single frequency,
- an ultra-wideband pulse (spectral content from 100s of MHz to several GHz), or
- a burst of many ultra-wideband transient pulses,

Note that all of the above EM environments could be radiated or conducted.

Alternatively, one could classify the IEME applied to a system by the nature of the *source* producing the environment. Such sources could range from very unsophisticated EM noise sources like a spark gap or a Jacob's ladder discharge, to highly sophisticated directed EM weapons.

A third approach for classification of IEME is by examining the *effect* that such an environment could have on a system. Such effects can range from momentary loss of function of a system to catastrophic failure of the system due to component damage.

In this paper, we will examine each of these IEME classification techniques and suggest one which is most useful in attempting to understand the effects of such environments on electrical systems.

II. IEME Classification By Environmental Attributes

The most common EM environment that affects electronic systems is naturally occurring lightning. In regions of high lightning activity, surge protection devices and lightning rods are commonplace. In addition, many military assets and a few civilian systems (e.g., nuclear power plants, communications facilities, etc.) in some nations are protected against the damaging effects of the High-Altitude Electromagnetic Pulse (HEMP) [1, 2].

The emerging high power electromagnetic (HPEM) environments, which could be used intentionally to disrupt a system and which are the subject of this paper, are also of concern for system protection. To describe these diverse EM environments qualitatively, Figure 1 shows typical spectral magnitudes of the incident E-fields as a function of frequency. In this plot, the continuous spectra from natural lightning [3] and HEMP spectra are noted, together with higher-frequency wide band spectra from the so-called ultra wideband (UWB) EM pulse environment. In addition to these continuous spectra, there are various narrow band signals that are often referred to as "high power microwave" (HPM) environments.

A. IEME Characterization by Spectral Attributes

These latter two IEME environments can be divided into four categories, based on the frequency content of their spectral densities as "narrowband", "moderate band", "ultra-moderate

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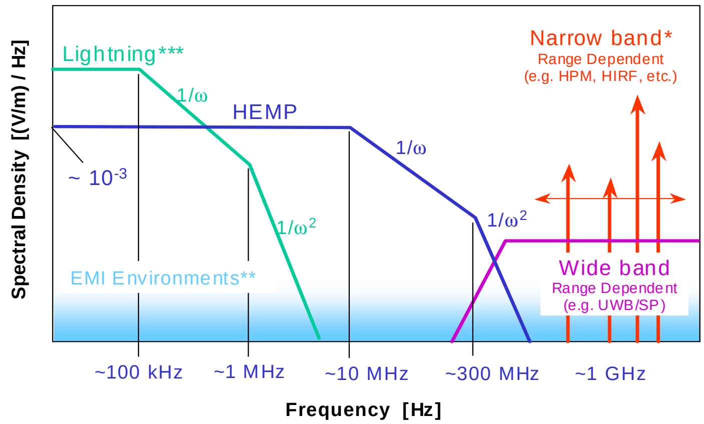
band" and "hyperband"[1]. To characterize these environments, we define the *bandratio* of the EM spectrum as $br = (f_h / f_\ell)$. Using the inherent features of *br* in a manner consistent with the emerging EM field production technologies, we propose the definitions for bandwidth classification presented in Table 1 [4].



Notes: * narrow band extending from ~ 0.5 to 3 GHz
** EM noise environments, not necessarily HPEM
*** significant spectral components up to ~ 20 MHz, depending on range

Fig. 1. Comparison of the spectra of several types of EM environments.

TABLE 1
IEME CLASSIFICATION BASED ON BANDWIDTH

Band type	Percent bandwidth $pbw = 200\left(\frac{br-1}{br+1}\right)$ (%)	Bandratio *br*
Narrow or hypoband	< 1%	< 1.01
Moderate or mesoband	1% < *pbw* ≤ 100%	1.01 < *br* ≤ 3
Ultra-moderate or sub-hyperband	100% < *pbw* < 163.4 %	3 < *br* ≤ 10
Hyperband	163.4% < *pbw* < 200%	*br* ≥ 10

Typically, the low and high frequency limits are 3 dB down from a flat spectrum. Not all spectra are "flat"; consequently, for waveforms with uneven spectra, the criterion for the finding f_ℓ and f_h could be based on the energy content in a certain spectral interval [5], as follows. One can find $\Delta f(f_h, f_l) = f_h - f_l$ such that $\Delta f(f_h, f_l)$ becomes minimal. Using the norm nomenclature this is expressed as

$$\frac{\left\|\tilde{V}(j\omega)\right\|_{\omega,2}^{\omega_h,\omega_l}}{\left\|\tilde{V}(j\omega)\right\|_{\omega,2}} = 0.9;$$ with the window norm defined as

$$\left\|\tilde{g}(j\omega)\right\|_{\omega,p}^{\omega_1,\omega_2} \equiv \left[2\int_{\omega_1}^{\omega_2}\left|\tilde{g}(j\omega)\right|^p d\omega\right]^{(1/p)} \quad ; \ \omega = 2\pi f \qquad (1)$$

This definition insures that 90% of the overall energy is contained in the interval (f_ℓ, f_h). Baum and Nitsch [5] also suggest a weighted norm as an improvement over the above definition in estimating the interval (f_ℓ, f_h).

Furthermore, for spectra with a large dc content (such as the early-time portion of the NEMP environment, one just has to calculate f_h, determine the number of decades (expressed as the bandwidth decades *brd*) from 1 Hz to f_h Hz, and then calculate $br = 10^{brd}$. In other words, we stipulate the lower limit to be 1 Hz if the spectrum has large dc content.

It is observed that the proposed classification presented in Table 1 is different from two other classifications in the literature [6, 7]. DARPA [6] defines ultra-wideband signals with a *pbw* > 25%, while the FCC [7] defines ultra-wideband signals with a *pbw* > 25% or with an overall bandwidth of 1.5 GHz. There have been requests from industry to the FCC to lower the overall bandwidth to 500 MHz, regardless of center frequency. Because of the nature of the emerging technologies, (e.g., Impulse Radiating Antennas (IRAs) with a *pbw* >190%), we believe a 4-band classification scheme given in Table 1 is more appropriate.

B. *IEME Characterization by E-Field Strength and Other Attributes*

Another approach for characterizing the IEME produced by a HPEM source is to examine the E-field strength at a specified distance from the source, the frequency agility of the source, the duration and repetition rates for pulsed sources, and the burst lengths. For IEME frequencies in the range of 200 MHz to 5 GHz (λ varying from 150 cm to 6 cm) the feed and antenna structures for the radiating systems typically consist of electromagnetic horns and reflectors, so aperture antenna theory provides some information about the radiated EM field behavior.

Typical rms CW source powers from readily available sources can range from 1 kW (for a simple microwave oven source) to over 10 MW (for radar tubes). The antenna aperture area is $A \le 10$ m^2, which is a practical sized antenna that can be truck mounted and be driven under overpasses and on bridges). For such an aperture antenna, the peak E-field in the aperture of the antenna is: $E_o = \sqrt{P Z_o / A}$, where Z_o is the impedance of free space. The peak radiated E-field at a distance *r* is given as $E_f = E_o A/(r\lambda)$.

It is convenient to define the "far voltage" as the range-normalized radiated E-field $V_{far} = r E_f$. For an assumed aperture area $A = 10$ m^2, the aperture E-field and the far voltage for two antenna power levels are shown in Table 2.

[1] Note that this terminology is consistent with that being developed for IEC 61000-2-13 Standard, entitled "EMC, High-power electromagnetic (HPEM) environments -- radiated and conducted (Draft)".

TABLE 2

APERTURE FIELDS AND FAR VOLTAGES

Qty.	**Peak Power = 2 kW**				**Peak Power = 20 MW**			
	0.5 GHz	1 GHz	2 GHz	3 GHz	0.5 GHz	1 GHz	2 GHz	3 GHz
Aperture field E_o	274 V/m	274 V/m	274 V/m	274 V/m	27.4 kV/m	27.4 kV/m	27.4 kV/m	27.4 kV/m
Far voltage $r E_f$	4.57 kV	9.13 kV	18.27 kV	27.40 kV	457 kV	913 kV	1.83 MV	2.74 MV

From the data in Table 2, we can estimate the electric field levels as a function of frequency and range for the two chosen power levels. This leads to the results provided in Table 3 for radiated E-fields, which indicate that with modest sized antennas and readily available microwave sources, it is possible to produce on-target E-fields greater than 100 V/m at kilometer distances. Considering the possible effect of these fields on illuminated equipment, the L-band frequency range is likely to cause more electronic damage than at the higher frequency bands (10 GHz radar for example) [8].

TABLE 3

RANGE OF RADIATED ELECTRIC FIELD AT VARIOUS FREQUENCIES AND TWO DIFFERENT POWER LEVELS

Frequency	**Range**	**Antenna aperture of 10 m^2 and output power of 2 kW**	**Antenna aperture of 10 m^2 and output power of 20 MW**
500 MHz	300m 1km	15.23 V/m 4.57 V/m	1.52 kV/ m 457 V/m
1 GHz	300 m 1 km	30.43 V/m 9.13 V/m	3.04 kV/m 913 V/m
2 GHz	300m 1km	60.90 V/m 18.27 V/m	6.09 kV/m 1.83 kV/m
3 GHz	300m 1km	91.33 V/m 27.40 V/m	9.13 kV/m 2.74 kV/m

C. Realization of IEME Sources

1) Hyperband Systems

In the context of hyperband HPEM systems, TEM horns and reflectors fed by TEM transmission lines have been established as efficient radiators. For example, half-cycle and single cycle sine wave generators at 1 GHz, with amplitudes of 100 kV (peak to peak) are realistic and practical sources [9]. One could consider a single TEM horn antenna for radiating such a pulse. Calculations of the TEM horn radiation indicate that a source-normalized far-voltage response from the antenna (rE_f /V) of about 0.5 is typical.

Such an antenna is not necessarily an optimal design. This means one could produce an impulse-like signal with amplitude of about 50 V/m at 1 km with a hyper bandwidth spectrum.

The parameter space for developing a hyper-bandwidth system from commercial components includes the following:

- Source waveform: a half-cycle or full-cycle sine wave
- Amplitude: 100 kV peak-to-peak for full cycle, 50 kV for the half cycle
- Center “frequency”:1 GHz (nominal)
- Bandwidth: 100 MHz to a few GHz
- Antenna type: TEM horn
- Antenna volume: 30 cm x 30 cm x 30 cm (1 wavelength in each dimension)
- Peak field at 1 km distance: ~ 50 V/m (time domain peak)

As in the case of narrowband sources, it is possible to array the hyperband sources and antennas. The time domain field at early times is additive. For example, a 3m x 3m array could contain about 150 elements and the peak signal can reach up to 7.5 kV/m at a distance of 1 km.

2) Narrowband (Hypoband) Systems

For the production of narrowband (or hypoband) IEMI, a radiating system referred to as a “Phaser” can be used. This refers to a device that produces **P**ulsed **H**igh-**A**mplitude **S**inusoidal **E**lectromagnetic **R**adiation. A progression of potential Phaser designs is referred to as Mark N Phasers, and is defined by source powers of 10^N GW [10]. Thus a Mark 0 Phaser has a power out from the source of 1 GW. The power out of the source is typically referenced to the lowest order waveguide mode which can be coupled into a pyramidal horn antenna as described in detail in [10]. A good example is a relativistic magnetron source that is commercially available [11] with the following capabilities.

- Frequency: 1.1 GHz
- Peak power: 1.8 GW (average power = 0.9 GW)
- Pulse width: 60 ns (containing 66 cycles)

This commercial source can easily be modified to produce an average power of 1 GW, with slightly increased pulse duration of 100 ns to contain greater than 100 cycles of L-band sinusoidal signal. With an antenna having an aperture area of about 10 m^2, it is estimated that such a system could easily produce fields of ~ 2.3 kV/m at 3 km and ~ 700 V/m at 10 km. Such narrow band generator systems could also be truck-mounted and arrive in close proximity to civilian electronics systems and facilities, producing much higher field levels.

Several narrowband generator systems in the frequency range of 0.7 GHz to 3 GHz exist. Examples include:

- The Swedish Microwave Test facility in Linkoping, Sweden,
- The Orion system in U.K., which uses relativistic magnetrons and horn-fed reflector antennas [12],
- A Super Reltron – based system in CEG, Gramat, France, called the Hyperion, and
- A Super Reltron – based system at WIS, Munster, Germany.

It is noted that these systems are used in studying the vulnerabilities of electronic systems. However, some smaller-scale versions of such systems could be used for destructive purposes, if acquired by organizations/groups intent upon harming civilized societies. Therein lies the potential threat in the present context of civilian electronics systems and facilities.

3) Moderate Band (Mesoband) Systems

The term "Dispatcher", standing for **D**amped **I**ntensive **S**inusoidal **P**ulsed **A**ntenna, **T**hereby **C**reating **H**ighly **E**nergetic **R**adiation, is an example of a moderate-band radiating system. While the Phaser is a narrowband device in which about 100 cycles of a single frequency radiation are produced in each pulse, Baum [13,14] has described Dispatcher systems that consist of a damped oscillator integrated into an antenna system.

Examples of such a system are: (a) a low–impedance quarter wave transmission line oscillator feeding a high-impedance antenna, and (b) a low-impedance quarter wave transmission line feeding a TEM fed reflector.

The transmission line oscillator consists of a quarter wave section of a transmission line (perhaps in oil or high-pressure gas medium for voltage stand off) that is charged by a high voltage source and a self-breaking switch across the transmission line. When the switch closes, a pulsed signal is fed into the antenna connected to this transmission line that radiates an HPEM signal. As an example, 500 MHz corresponds to a quarter wavelength in transformer oil of 10 cm, which is very compact. The charge voltages can be in the range of 100s of kV. The half wave section doubles the length for a given frequency and thus increases the stored energy. This is included here as an emerging system that may be used in creating HPEM environments on electronic systems such as the civilian electronics systems and facilities.

The above discussion of types of IEMI sources is by no means complete, as there are many laboratories and organizations world wide that are developing and using such sources. The interested reader is referred to refs. [15] and [16] in this special issue for additional details.

III. IEME Classification by Source Technology

Another way of categorizing IEME environments is based on the level of sophistication of the underlying technologies involved in producing the EM environment, as low, medium and high-tech systems. The low-tech systems are characterized by: i) marginal performance, ii) minimal technical capabilities and iii) easily assembled and deployed while hiding behind dielectric walls in trucks and similar vehicles. In contrast, medium-tech systems require the skills of a qualified electrical engineer and relatively more sophisticated components such as a commercially available radar system that can be modified to become a weapon system. More sophisticated high-tech and high-power electromagnetic (HPEM) systems would require specialized and sophisticated technologies and perhaps even specifically tuned to cause severe damage to a specific target.

A. Low-tech generator systems

Due to its simplicity, a readily available low-tech CW microwave source in the S-band (2.45 GHz) is the magnetron in a microwave oven. Typical and readily available microwave ovens are rated at 800 W to 1,500 W of rms continuous microwave power. With 1,100 W of rms continuous microwave power at 2.45 GHz from a microwave oven, the peak electric field in the output waveguide is about 25 kV/m. Starting from this E-field in the waveguide aperture (assumed to be a WR 340), far-field voltage factors (rE_{peak}) that are obtainable are listed in Table 4.

TABLE 4

RADIATED FIELDS FROM A MICROWAVE MAGNETRON [15]

Antenna type	**Power (rms)**	**Peak E-field in guide**	rE_{peak}	E_{peak} **(r = 0.3 km)**	E_{peak} **(r = 1 km)**
Open-ended WR 340	1,100 W	25 kV/m	540 V	1.8 V/m	0.54 V/m
Pyramidal horn	1,100 W	25 kV/m	2200 V	7.3 V/m	2.2 V/m
Reflector antenna (1.8 m dia.)	1,100 W	25 kV/m	4680 V	15.6 V/m	4.7 V/m

This low tech system was used in exposing several test objects such as calculators, wrist-watches, electro-explosive devices, florescent tubes etc., with significant adverse effects (upset and burn-out) [17].

B. Medium-tech generator systems

Commercially available radars can be modified to become an HPEM system (narrowband or ultra wideband, and this is an example of a medium-tech system. Examples of complete systems offered for sale by Radio Research Instruments Co., Inc. of Waterbury, CT are the AN/FPS-36, AN/FPS-71, AN/FPS-7, and AN/FPS-77.

The AN/FPS-71 search radar is chosen for illustrative purposes. Its salient electrical parameters are:

- Aperture area: 93.5 m^2
- Peak power output from the magnetron: 5 MW
- Average power from the magnetron: 2.5 MW
- Frequency of operation: 1.285 GHz
- L-band waveguide dimensions: longer dimension = 16.51 cm; shorter dimension = 8.26 cm
- Dominant modal impedance: 534 Ω
- Focal length of the reflector: 5 m (assumed)
- E-field on the aperture: E_a = 630 kV/m
- Far field rE product: rE_f = 6 MV

The (rE_f) estimated above implies that this commercially available system, which powered by a 5 MW magnetron source is capable of producing peak E-fields listed in Table 5.

TABLE 5

RADIATED PEAK ELECTRIC FIELDS

Range r	**Peak E-field (antenna area = 93.5 m^2)**	**Peak E-field (antenna area = 9.35 m^2)**
300 m	20 kV/m	6.3 kV/m
1 km	6 kV/m	1.9 kV/m
10 km	600 V/m	192 V/m

This commercial system has a large antenna aperture of 93.5 m^2. This area can easily be scaled down by a factor of 10, in which case the peak electric fields as shown in Table 5 decrease by a factor of $\sqrt{10}$. These levels are still significant with regard to system effects.

C. *High-tech generator systems*

The high-tech systems require specialized and sophisticated technologies in their construction. Examples of such IEME generators are the Impulse Radiating Antennas (IRAs) [18 – 21]. An Impulse Radiating Antenna (IRA) with a diameter of 23 cm is shown in figure 3.

Fig. 3. Impulse Radiating Antenna (IRA) with a diameter of 23 cm, a component of a high-tech IEMI system.

This antenna has been excited with a commercially available pulsed voltage source (pulser) having a peak voltage amplitude of 2.5 kV, a rise time of 100 ps, full-width to half-max (FWHM) pulse width of 2 ns, and a *prf* of 500 Hz. Examples of the on-axis radiated E-field from this antenna have been illustrated in ref. [19]. The above IRA is one of many that have been fabricated and tested, as listed in Table 6.

TABLE 6

EXAMPLES OF REFLECTOR IRAs

Name	Diam.	Pulser	rE_{peak}	*br*
AFRL, KAFB	3.66m	120kV	1.3 MV	100
AFRL, KAFB	1.83m	150 kV	690 kV	50
Swiss IRA	1.8m	2.8 kV	10 kV	50
TNO IRA	0.9m	9 kV	34 kV	25
U. of Magdeburg, Germany	0.9m	9 kV	34 kV	25

In accordance with the definition in Table 1, all of the high-tech systems listed in Table 6 are hyperband HPEM generators, since their band ratios are > 10. However, it is observed that they can also be turned into sub-hyperband generators by reducing the antenna diameter (which is seen to increase the lower cutoff frequency of the system) or by degrading the risetime of the voltage pulse into the antenna (which can be shown to lower the upper cutoff frequency of the radiated spectrum).

IV. IEME CLASSIFICATION BY TYPES OF EFFECTS

A third approach in classifying an IEME is to consider the possible effects that the environment might have on a targeted system. For the purpose of illustrating the consequences of such environments, one may choose a civil aviation example of an aircraft landing at a civilian airport [22].

As described in ref.[23], such an aircraft can be described electromagnetically as a shielded enclosure, much like a Faraday shield. However, such a shield is not perfect, and it is well established that sufficiently intense electromagnetic signals in the frequency range of 200 MHz to 5 GHz can cause electronic damage in this and many other types of systems due to imperfections in the shielding topology.

HPEM generators are effective in the aforementioned frequency range for the following reasons:

- There are deliberate antennas on the aircraft operating in this frequency range, which provide a path into the system (front door coupling paths),
- Typical apertures, slots, holes and hatch openings have their resonance in this frequency range (inadvertent or back-door coupling paths),
- Typical rivet spacing at the junction of two metallic surfaces at the skin level are about a quarter to a full wavelength in this frequency range (1 to 2 GHz),
- Physical dimensions of circuit boxes are themselves resonant in this frequency range (1 to 2 GHz), and
- The interior coupling paths (e.g., transmission lines, cables at a height above the ground plane), are roughly a quarter to a full wavelength in this frequency range (1 to 2 GHz).

Each of the above points give rise to EM energy deposited at potentially critical interfaces in internal circuitry in the aircraft, and as a consequence, the internal aircraft equipment can react in a variety of different ways[1].

A. *Noise (front door)*

Sensitive receivers in civilian electronic systems are designed to operate with E-field levels as low as several μV/m, within a narrowly tuned receiver bandwidth. It is very easy to overpower such signals by a decade or more of field strength. The user of the electronic device/equipment merely experiences noise in the receiver that lasts as long as the disturbing environment.

Consequences of this interference may not always be critical. In the worst-case scenario, the pilot aborts landing and makes another try or goes to an alternate airport.

B. *False information (front door)*

Once again with a decade or more E-field strength above the signal level, the intentional electromagnetic signal may be designed to feed false information to the receiver.

Consequences here may be critical, since the aircraft can land somewhere other than the runway.

C. *Transient upset (back door)*

It is noted that one requires several volts of induced signals to affect the logic state of an electronic component. At a frequency of ~ 1 GHz, an effective coupling height of 0.1m is typical for unhardened/open systems. This implies 10s to 100s of V/m of tuned narrowband environment is required to cause an effect. The pulse width is assumed to be such that the quality factor Q of the threat environment is greater than that of the victim system Q [24 – 26]. At the nominal frequency of 1 GHz, approximately 100 cycles or 100ns pulse duration should be sufficient. Consequences of this interference depend on system design for recovery and repetition of threat environment.

D. *Permanent damage (back door)*

For permanent damage to occur, semiconductor junctions must be exposed to over-voltages that result in breakdown. This phenomenon means that the bias on the junction is also a factor. At a nominal frequency of 1 GHz, this requires several kV/m [27] incident electric field strengths.

V. CONDUCTED IEME

It is to be emphasized that the IEME signals can be both radiated and conducted, and we have focussed on the radiated IEME in this paper. However, cconducted HPEM environments are also a potential threat to electronic equipment connected to power and communications lines [28 – 30].

In most modern buildings there is a personal computer on nearly every desk, and these computers are typically connected to the power supply and to a telephone cable or local area network (LAN). In the case of data communications, at the present time, most communications circuits that enter a building will pass through a router or switch before sending the data to individual equipment.

This suggests that this interface electronic equipment could be potentially vulnerable to HPEM conducted pulsed voltages and currents that may be transmitted into the building from the outside. For older installations, telephone lines enter a facility and are wired directly to individual telephones or computers inside. In this situation, internal electronic equipment could be damaged by externally injected HPEM pulsed voltages.

Conducted IEME signal can either be covertly injected on to power or signal cables are they may also be an induced environment due to a radiating IEME source.

VI. SUMMARY

In this paper, we have described three ways of classifying intentional electromagnetic field environments. The classification schemes are based on: (*a*) the frequency of coverage or the bandwidth of the EM signals, (*b*) the level of sophistication of the technologies required to produce the EM environment intended to cause damage to electronic systems, and (*c*) the possible effect that the EM environment might inflect on the targeted system. Illustrative example systems for each category are also discussed in this paper. It is our opinion that the first IEME classification scheme is preferred, as it is a quantitative measure of the environment, while the other two are more subjective in nature.

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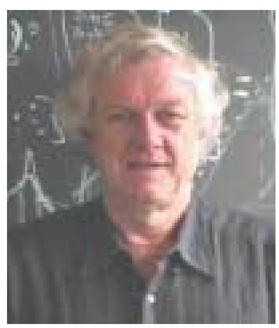

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